Senior Thesis

An Examination of Desert Geomorphology Throughout Geologic Time

by
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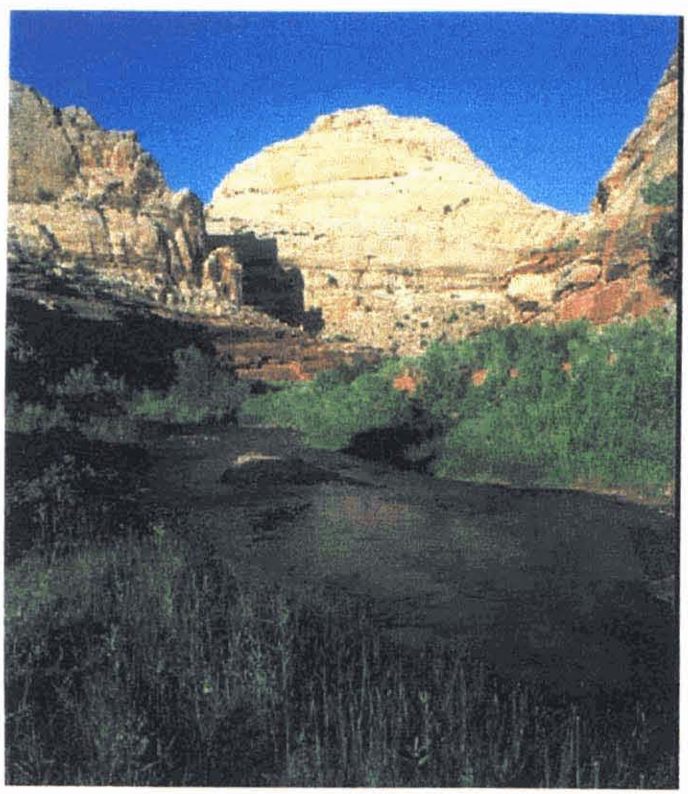

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Abstract

The aim of this paper is to describe the evolution of desert environments including descriptions of past, present, and future desert environments. The impressive Navajo Sandstone will serve as an example of deposits of a former desert which over time became lithified, whereas the Sahara Desert will serve as a modern example. As far as the future is concerned, aspects of modern desertification and mankind's role in it will be discussed.

Introduction

All across the planet Earth, natural processes mold and shape the planet into new manifestations each day. Knowledge of these processes, which act over time scales ranging from several days to millions of years, are an essential part of understanding the Earth and its history. One of the largest processes that has persisted across the millennia is that of desertification. In general people consider a desert to be a place devoid of life and vegetation with no obvious purpose except heat, death, and despair. Little do they know that deserts are not only the home to hundreds of plant and animal species, they also are a direct result of climate and regional changes that are diagnostic of arid lands.

In order to understand the past, present, and future of deserts and desertification one must first understand the processes by which features such as dunes, ripples, and interdune structures are created. Secondly, the stratigraphic record can be examined to find an example of what happens when a desert undergoes burial and lithification. Next a modern example, namely the Sahara Desert, will be discussed so that interpretations can be made from modern climate conditions. Finally the impact of climate and land overuse can be discussed to predict where and why future deserts will occur.

Desert Processes and Features

There are several factors that are necessary for the formation of a desert, of which climate and sand source are the most important for the purpose of this paper. In regards to sand sources two types of deserts can be formed. Sand-rich deserts have a plentiful sand source whereas sand-poor deserts have no readily available sand source. This paper will deal mainly with sand-rich deserts. The climate must be arid, with little to no rainfall per year, and have either high temperature or very cold, windy air to aid in moisture removal. Deserts are generally prevalent in the moisture-starved plains on the leeward side of a mountain chain. In this case, winds carrying moisture deposit rain and snow in the mountain chain due to temperature and pressure variations, leaving little to no moisture for the leeward side of the mountain. This area tends to have heavy wind activity with the mountains providing a steady sediment supply. In contrast, areas can still be subject to desertification but have no steady sediment supply. In these cases, the land simply becomes moisture-parched and barren of plant and animal species that require large amounts of water for survival. Additional information on these processes will be provided when discussing examples of deserts and eolian sandstones.

Grain Movement

In order to understand eolian transport of sand particles, the different modes of transportation must be examined. In general, wind transport is very similar to water transport except for the characteristics of the transporting medium. The first form of transportation is bed-load movement which, according to Pye and Tsoar(1990), includes the processes of saltation and surface traction. Saltation is the process by which grains move in a series of jumps. The length of the jump depends on the wind velocity, grain size, and grain shape. It has been proven that grains with higher sphericity and roundness provide less drag and travel farther in a series of jumps(Pye and Tsoar, 1990). Surface traction is defined as the process by which grains roll or slide across the dune surface. These two processes provide the main mode of transport for sediment in dune sands and played a significant role in the deposition of the Navajo Sandstone, which will be discussed later.

The next main form of transport is suspension, which is defined as airborne transportation of particles. In the case of the Navajo Sandstone the grains were too large to be transported in suspension unless the velocity of the wind was very high. As defined by Boggs(1995), a sand of medium grain size ranges from to 0.50 mm. According to Figure 1, this grain size is well above the size carried in suspension in the common velocity range of sand storms. From this it can be inferred that most of the deposition of the Navajo Sandstone was accomplished by bedload transport, except perhaps in extreme conditions.

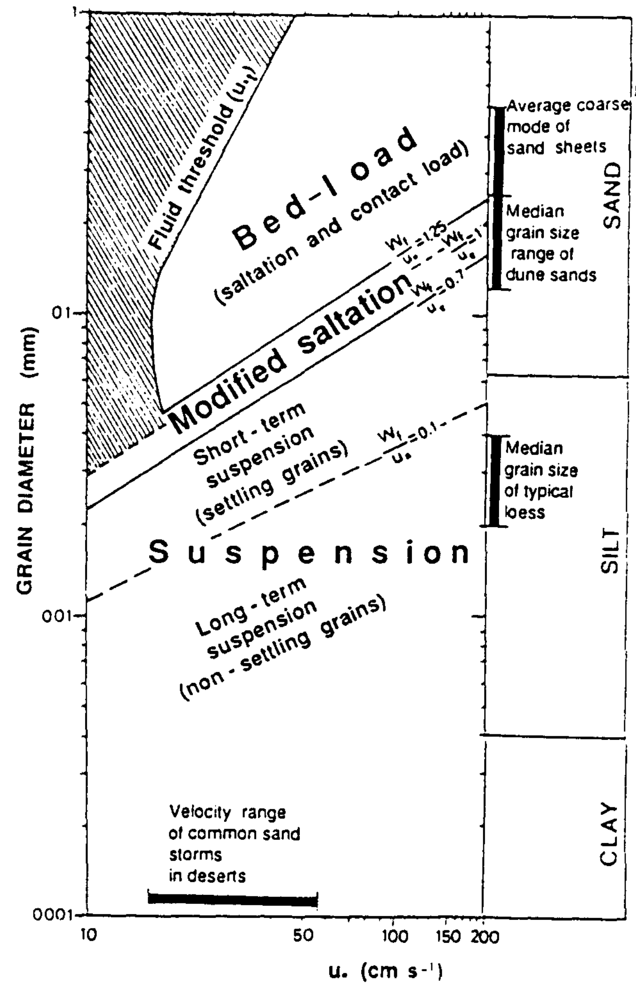

Figure 1: Grain Size vs. Wind velocity u* (Fig. 4.10 in Pye and Tsoar (1990))

Abrasion Processes

Before desert and dune features can be discussed it is important to provide relevant information on the abrasional processes which help to supply sediment to the desert. The processes by which wind erodes can be defined as deflational, where unconsolidated sediment is entrained, and as abrasional, where cohesive material is worn down (Cooke et al., 1993). These concepts can be combined to show exactly how consolidated rock can be worn down by the wind.

The actual process of abrasion is quite simple. Airborne particles are carried or saltate until impact with another object occurs. Several variables must be considered when discussing these impacts. Factors such as wind velocity, grain size, target (a cohesive rock) durability (includes density, mineral hardness, induration, existing fractures) and airborne grain size and hardness will affect how much erosion can occur. For example, slow wind velocities or hard target rocks will result in low erosion rates, whereas high wind velocities and a poorly indurated target rock will result in high erosion rates. In all actuality the wind speed would have to increase up to 200 mph to cause suspension of most grains(Pye and Tsoar 1990).

In addition to wind velocity and grain size, several other factors must be considered as affecting abrasion rates. First of all, a constant grain source must be available for the abrasion to persist. Second, these grains must not be in high concentration. This would cause loss of kinetic energy by grain to grain collision which would lessen the force of the impact on the target rock. Finally, the surface being abraded must be inclined less than 90 degrees for erosion inducing impact (Cooke et al., 1993). This is important because the grains can cause more damage to existing fractures and chips by impacting at a low angle than at a higher one.

Dunes

The most distinctive of all desert features are dunes. A dune, as defined by Cooke et al. (1990), is a subaerial body of sand 30 cm to 400m tall and 1 m to 1 km wide that is shaped by wind conditions and placement of sand particles. Despite the huge range stated in the definition sand dunes at the lower margin of the defined size would not persist in a variable speed wind environment and would probably disperse, grow, or accrete to another dune.

The two main types of dunes are stationary, which do not move, and migratory, which change location as the wind blows. Stationary dunes are always characterized by having an anchoring landform such as rock outcrops or plant life(Cooke et al., 1993). Dunes caught on plants most likely will occur in marginal desert environments such as sabkas and at the base of a leeward mountain slope.

Migratory dunes can also be subdivided into several categories; the most common are transverse dunes and linear dunes. Transverse dunes are dunes with short lengths, long widths, and variable heights (Cooke et al., 1993). They generally have a gently sloping windward side and a steeply sloping leeward side. This type of dune will be the main focus of the discussion of dune dynamics in this paper. Linear dunes grow by extension down-wind and are oriented near-parallel to oblique to the wind (Cooke et al., 1993). These dunes are steeper than transverse dunes and usually asymmetrical.

The origin of a dune would seem to be an easy question that should result in an easy answer. Where does a dune come from? Obviously from accumulated blowing sand. Despite this, there is a bit more explaining that has to be done to fully answer this question. Cooke et al (1993) explains the dune-forming process as occurring in one of two methods. The first method is by sand accumulating in different surface levels. Small pits, hollows, and even small bumps can cause accumulation by altering the velocity of the wind. Wind speed will drop when entering a hollow or climbing a slight rise due to resistance and friction. This decrease in speed causes grains, which have been in transport via suspension and saltation, to drop out and fill or cover the area. Once these areas are filled or covered, the process will continue because the sand moves with shifts in wind velocity. Eventually slight sand ripples will grow to dune size, hence forming dunes.

Several variables must be considered as affecting the dune formation process described above. First of all this model requires a relatively consistent wind direction. Drastic shifts in wind direction would cause excessive erosion and alteration of the shape of the dune. Another similar variable for consideration is wind velocity, which could also cause an increase in erosion. When combined, a drastic change in wind velocity and/or direction could cause various changes in dune dimensions.

The second process by which dunes are shaped is quite simple. First a stationary dune must develop. Then, when wind speeds or sliding of grains on the dune increase to more than the anchor can hold, the dune will slowly migrate off its anchor and become a migratory dune. Stationary dunes with strong anchors will simply decrease in size or disaggregate completely when wind velocities increase enough to disperse individual sand grains.

The next aspect of dune activity that must be examined is the process by which transverse dunes migrate and replicate. As wind travels up the windward side of a dune, particles of sand are taken into saltation as well as pushed off of the peak of the dune. These pushed particles can create avalanches of grains that slowly pile up on the leeward side of the dune. Other particles can continue to saltate to the next dune where they may either stop or move on, depending on the wind velocity. Not all saltating particles stop at each dune. Particle size, being variable, will dictate a grain's movement from dune to dune. Heavier grains will saltate smaller distances or remain as bedload, while smaller grains will achieve longer leaps. This is an ongoing cycle in which grains migrate from dune to dune as long as wind velocities remain strong enough. The cycle is continuous so that dunes stay at or grow to an equilibrium size depending on the wind speed(Cooke et al., 1993). The amount of grains that blow off a given dune is about equal to the number accreted onto the dune when it is in equilibrium. In contrast, this equilibrium size will change when wind velocity or direction change therefore causing the dune to alter size and shape to reach a new equilibrium.

Dune replication occurs in much the same fashion as dune migration. As wind speeds change variably, the sizes of dunes will also change. Shifts in wind direction can cause the dunes to form a distorted shape (much like 3-D ripples), which can force a portion of the dune to break off and migrate on its own. This dune, if given enough space, will grow on its own and undergo the same accumulation/erosion process that affects the other dunes.

Ripples and Interdune Features

Ripples are a common desert feature, and tend to occur on the windward side of transverse dunes. Ripples, like dunes, vary in size with wind speed and grain size and form from the same processes as dunes, except at a smaller scale. Several models of ripple formation have been introduced of which one is generally accepted today. This model, the "ballistic model", was first introduced by Bagnold (1941). This model suggests that ripples will form when grains are deposited one saltation length downwind from a depression or obstruction that they hit on the dune surface. This process continues until a ripple is formed. Some potential problems exist with this model. For example, if the saltated grains are not of the same size, or if the wind speed does not remain constant, then the grains could land in a near-random pattern. Since ripples are relatively small dune features and they form over a short period of time, however, these problems appear to be overcome during ripple formation by short term consistency of wind speed and sediment size supplied. As it was explained earlier, grain movement depends on the size of the grain and the speed of the wind. Ripples usually contain a relatively consistent grain size so at a constant wind speed these grains would saltate at a reasonably equal distance, not in a random pattern as stated by the ballistic model. This process, the ballistic model, was later revised to account for these variables, and become an acceptable hypothesis. Since this process mimics that of dune formation it is obvious that ripples are subject to the same migration and equilibrium patterns that dunes are.

Other structures than can be seen inside of dunes (in cross-section) include truncation surfaces and slipface strata. Truncation surfaces are surfaces to which a dune was at one time was eroded, either by a sandstorm or by large dune movement (Cooke et al., 1993). These surfaces are commonly referred to as bounding surfaces and planes. One type is known as a super-truncation surface, and can be recognized as a complete pause in dune formation as the result of an erosional event. In this case a paleosol usually develops on this surface. Other types of truncation surfaces are classified as being first, second, or third order. First order surfaces are formed by the passage of large dunes, tend to be low angle, and are laterally extensive. Second order surfaces have the same characteristics as first order surfaces, except they gently dip and are caused by the migration of medium dunes. Third order surfaces are formed by daily and seasonal erosion as well as wind direction change (Cooke et al., 1993).

Slipface strata, also known as cross-stratification or foreset strata, fall into two categories. The first, sandflow strata, are formed when a stream of sand falls from atop a dune crest, forming a long lenticular sandflow on the leeward side of a dune. The second, slump strata, are formed when coherent bodies of sand slide down a slipface forming a larger sheet of sand on the leeward side of a dune.

Lithification of Desert Deposits

In order for a sequence of desert deposits to become lithified several things must happen. First of all, there must be a continuous source of cement or multiple discontinuous stages of cementation, which will intermingle with the sand grains, forming a cohesive bond upon burial. Second of all, the desert deposits must remain long enough (i.e., the deposits are not reworked) to be buried and lithified.

Most eolian sandstones have a carbonate cement, which is indicative of a nearby calcareous environment. Consequently, the existence of an ocean, inland sea, or extensive lake would provide enough carbonate from its beaches and carbonate enriched groundwater. This carbonate sand can interfinger with the desert sand and cause lithification of the deposit under certain circumstances. If the desert is by a body of water, offshore storms can drench the sands, slowly dissolving the carbonate and instigating a slow cementation process (Cooke et al 1993).

If the desert is not located near a body of water, or if the prevailing winds blow in the wrong direction, cementation can occur another way. Subsequent burial of the dunes due to a constant sediment influx will eventually bury sand layers to the level of the water table. Any carbonate present in the deposit will be dissolved, then shifts in the level of the water table over time will precipitate the carbonate to form a grain to grain cement. Furthermore, most water will eventually be removed by pressure once the sand has been buried deep enough allowing any carbonate in the water to precipitate onto the grains. This can also occur with other types of cement. Carbonate is used as an example because it is most important towards deposits described in this paper. One thing that must be realized is that this is a gradual process which takes an amount of time unfathomable by the average human.

Desert of the Past: The Navajo Sandstone

Now that the basic morphology of deserts has been discussed it is important to examine a desert of the past that is currently exposed in the stratigraphic record. Throughout southern Utah, some of the most impressive rock outcrops are those of an eolian formation called the Navajo Sandstone. These Navajo outcrops include those in many of Utah's National Parks, such as Zion National Park, Coral Reef National Park, and Arches National Park. This formation originated in the Early Jurassic as a result of heavy wind erosion of an undetermined source rock.

Another outcrop form of the Navajo Sandstone is the popular "slickrock" outcrops near Moab, Utah, where both wind and water erosion have shaped the rock into round forms. The term "slickrock" originates from the smooth form of the outcrops and the general absence of soil, creating a barren "slick" rock. This type of rock is particularly popular for mountain biking because it provides a formidable challenge to riders.

In order to properly analyze the Navajo Sandstone, the first thing to be discussed will be its origin as indicated by its characteristics and sedimentary structures. It is important to examine the origin to determine possible parent rocks, climate conditions, and the relationship of the Navajo Sandstone to stratigraphically older and younger rocks. Characteristics of the Navajo such as grain size, color, and grain roundness, can also help determine these factors. Of utmost importance are the sedimentary structures, which will provide important information when discussing the eolian processes that formed the Navajo Sandstone. Much can be learned about important environmental factors such as wind speed and patterns from sedimentary structures such as ripples, cross-bedding, and silt lenses.

Extent and Stratigraphy

The paleogeographical setting of the Navajo Sandstone was quite typical for an eolian system. During the Early Jurassic, North America was located just to the south of the equator and the area known now as Utah was low and relatively flat (Barnes,1978). To the west there existed a shallow sea, so it is interpreted that the Navajo Sandstone was deposited in an area of low-coastal plains. Due to easterly prevailing winds and a possible mountain chain to the east, these plains were slowly turned into an arid desert. Due to the position of North America during the Jurassic, it has been determined that areas to the present day northwest of the Navajo Outcrops (NW Utah and E Nevada) are the areas from which the sediments were derived to form the Navajo Sandstone. Since this area is missing stratigraphic sections of Upper Triassic formations, it is possible that the Navajo originated from these missing units (Averett, 1987).

In order to understand the environmental conditions under which the Navajo Sandstone was deposited, it is also important to look at both older and younger units. Stratigraphically below and conformable with the Navajo Sandstone lies the Kayenta Formation, a tan to gray medium grained sandstone containing lenses of conglomerate (Averett, 1987). This sandstone was deposited in a terrestrial environment as indicated by freshwater gastropods and plant fossil remains. It can be inferred that the Navajo Sandstone was deposited after the climate changed from conditions that existed during deposition of the Kayenta Formation. Since the Kayenta Fm. was most likely deposited by a deltaic system, it is obvious that the climate became increasingly warm, and that fresh water sources dried up as evaporation exceeded precipitation. (Averett, 1987). Stratigraphically above the Navajo Sandstone lies an unconformity, which marks a time of widespread uplift and erosion, possibly including erosion of a portion of the Navajo.

Composition and Sedimentary Structures

The Navajo Sandstone has a relatively uniform composition throughout its entire geographic extent. It is described as a massive, gray to orange, poorly indurated, fine-grained, calcareously cemented quartz arenite in outcrop in NE Utah(Averett, 1987). Alternatively, it is described as a white sandstone with tints of red and yellow in the Glen Canyon area. Very obvious here is the poor induration, which Barnes(1978) describes as having "strength, texture and cohesion...such that the rock cannot support its own weight except under compression" He also notes that when undercut, the rock collapses into near vertical planes, which explains why the Navajo outcrops as sheer cliffs. Thicknesses range from 2000 to 3500 feet in the southwest, while the deposit thins to the northeast.

As Jurassic environments in the area became more arid, sand supplied from areas then located to the east began to be deposited. Over the next several million years (age 195-170 m.a.), the blowing sand formed a vast erg of dunes that filled the basin. Averett(1987) describes the deposition as an influx of gigantic sand waves, ranging from 40 to 50 feet high. It is believed that up to 50 sets of these waves were deposited, with each set eroding a portion of the previous one. This erg covered what is now known as the Colorado Plateau in a complete blanket (Averett, 1987).

The Navajo Sandstone contains sedimentary structures typical of eolian deposits. Tabular planar cross-beds, which usually are predominant in dunes (Boggs, 1995), are very prominent in the Navajo.Sandstone. As the sand was deposited, it formed layers of low angle laminae that eventually built up enough to form great dunes. In the lithified dunes that can be examined today, these laminae form long, sloping cross-beds, which cross-cut each other tangentially (Chronic, 1990). This type of cross-cutting indicates not only deposition but also slipping. As each bed was deposited, the weight distributed on the bottom layers caused slippage, with the laminae sliding to a more stable position. This slippage is indicated by internal truncation, or bounding surfaces within the dunes which, in this case, are typically of first or second order. The foresets of these dunes indicate wind direction, which as mentioned before was from the east in the past and from the northwest now.

The Navajo Sandstone also exhibits and wide variety of ripples. These include the prominent 2-D ripples, which in this case tend to be low-amplitude and, in some cases, climbing (Averett, 1987). Also apparent are wavy 2-D and 3-D ripple forms that indicate multi-directional wind flow. The causes and implications of these forms will be discussed in the next section.

One sedimentary feature of the Navajo Sandstone that is very important for interpreting its depositional setting is the presence of materials other than the normal Navajo sand. Some areas contain deposits of cherty limestone that formed in ephemeral, or short lived, seas, presumably formed by storms coming off the nearby sea (Averett, 1987). It can be inferred that most of the calcareous cement contained in the Navajo Sandstone was derived from these seas, especially by considering the induration of this sandstone. Sandstones deposited in a carbonate-rich environment tend to be very well cemented, while those deposited in an environment with a considerably less amount of carbonate would probably be poorly cemented. In this case the Navajo Sandstone probably was cemented by dissolution of the limestone lenses, which subsequently were partially replaced by quartz. Since the inland seas were short-lived, the total amount of carbonate deposited was relatively low and only a small amount of cement could be accreted to the sand grains during lithification. Averett(1987), in his coverage of the Jurassic, also indicates that after the formation of the unconformity surface that overlies the Navajo

Sandstone, most of the basin was invaded by a shallow sea. This sea may have provided more calcareous material to aid in the lithification of the Navajo Sandstone.

Another depositional feature of the Navajo Sandstone is the presence of silt and clay layers in interdune areas (Chronic, 1990). These deposits provide additional evidence that the depositional basin was not entirely dry. In general, there are two ways in which these layers could have been deposited. The first, and least likely, is the deposition of suspended of dust particles. As wind speed drops in the lee of a dune, the suspended particles can be deposited in the interdune areas. The more practical explanation of these layers is that small lakes formed from periodic storms coming from the ocean or the mountains. As the rain fell across the dunes, the water took smaller particles into suspension and then pooled in the interdune areas. After the storm passed, the particles settled and evaporation left behind a thin, muddy layer. Subsequent deposition of sand buried the muddy layer and preserved it in the stratigraphic record. Since all known occurrences of these clay and silt beds are thin, discontinuous, and horizontal, it can be inferred that most of the storms were relatively small and produced only small interdune lakes.

Eolian Processes

Now that the characteristics and sedimentary structures of the Navajo Sandstone have been described, it is possible to interpret the eolian processes that formed the dunes. Of primary importance are the dynamics and sources of the wind. Pye and Tsoar(1990) note that winds are caused by pressure and temperature variations. In the case of the Navajo Sandstone it is believed that the wind came from the east over higher elevation and more active storm areas. This could have been caused by several reasons. First, the area of higher elevation was probably cooler than the lowland desert. With the desert being completely open to the sky and sun due to lack of vegetation, with few storms, it would have been hotter than the mountainous area. This created a temperature differential that caused air to travel from the cool area to the hot area (Pye and Tsoar, 1990). Another analogous reason would be the pressure differential caused by the fluctuations in temperature.

It has already been established that the main type of bedding in the Navajo Sandstone is tabular-planar cross-beds, with some occurrences of trough cross-beds. Most of the cross-bed sets in the Navajo Sandstone consist of low angle beds which are indicative of higher velocity air flow. The angle is measured between the foreset laminae, which represent the slip faces of the dunes, and the horizontal. These laminae were deposited when overburdened sediment on the dune tops fell down the leeward side of the dune. The limited trough cross-bedding occurring in the Navajo most likely was caused by alternating wind direction and/or wind velocities, as well as crest migration.

Formation of the 2-D ripples indicates that a single wind direction dominated transport. Since the ripples of the Navajo are low amplitude, high velocity is interpreted. These ripples can be differentiated from one another in the outcrop form by the variation in bed laminae. Ripples generally form on dune faces that face into the wind. These ripples are formed the same way that dunes are by pushing grains upon one another until ridges form. These ridges are relatively low angle on the windswept side, while they are steeper on the other side.

Both wavy 2-D and 3-D ripples are indicative of multiple wind directions. As the wind blows in different directions, the crests of the ripples are altered into wavy and convoluted forms. As erosion continues, crestlines can be warped even further to form 3-D ripples when the crestline is no longer continuous. These can be seen in the Navajo Sandstone as trough cross-beds (USGS Bedform Sedimentology Site).

Outcrop Examples

It has already been noted that the Navajo Sandstone tends to outcrop as large cliff faces due to its poor induration. Only when these outcrops are seen can the extent and thickness of this deposit be understood. Figure 2 is an example from the USGS Bedform Sedimentology site which shows the massive cross-beds formed by dunes.

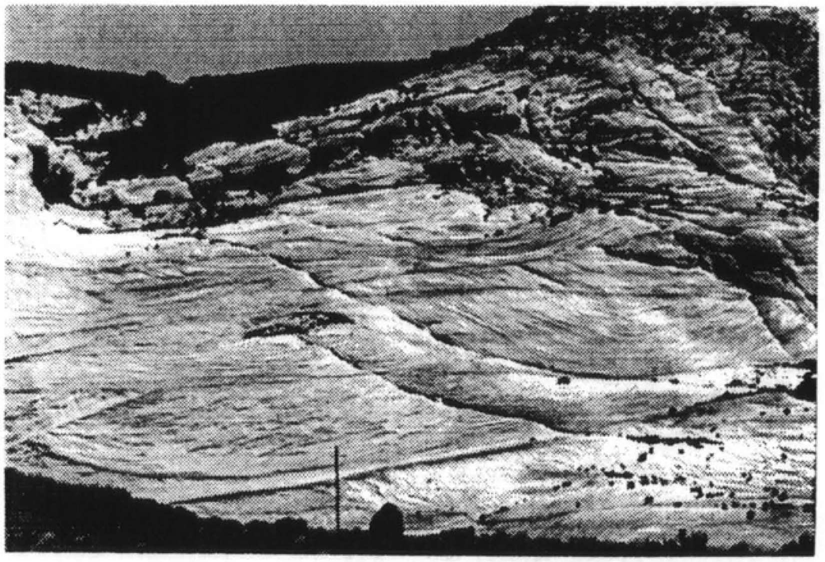

Figure 2

Figure 3 shows two dunes sets, one on top of the other. The bottom dune migrated from left to right, with ripples (most likely 3-D) migrating obliquely up and down slope. *Also from USGS web site

Figure 3

Desert of the Present: The Sahara

No other desert in the present world can compare to the vast expanse of the modern day Sahara. Covering an area of ~ 7 million square kilometers this impressive environment covers almost half of the African continent (Cooke et al 1993). Unlike the area where the Navajo Sandstone was deposited, the Sahara remains dry due to northeasterly airstreams which descend upon the area carrying little to no moisture. Measurements indicate that less than 400 mm of moisture falls on the area per year. This, combined with a high plant transpiration rate and a high surface evaporation rate due to high temperatures, creates the arid, moisture-free environment of a desert.

Due to the location of the Sahara Desert, the region is subject to the erosional forces of prevailing winds throughout the year. From November through April the region is subject to winds coming from the northwest and the Northeast whereas the rest of the year the winds only come out of the northwest. Upon examination of a geologic map (Chanteuex et al,1976) and an atlas map (Shupe , 1992) of the region several sediment sources can be found for desert system. One of the most prominent sediment sources are the Atlas Mountains, which lie on the northern coast of Algeria and Tunisia. These mountains are composed mainly of Mesozoic sedimentary units and are probable sources for the vast ergs that cover north-central Algeria and parts of Libya. This sediment source, as well as smaller outcrops of igneous rocks on the western edge of Africa, provide the sediment for the western and northwestern ergs.

Other major sediment sources are not on coasts but are instead located in the interior of the desert. The Ahaggar Mountains and the Tarazit Massif of the west-central Sahara consist of massively faulted Precambrian igneous through Silurian sedimentary rocks. Farther east, the Precambrian through Ordovician rocks of the Tihesti Mountains also fuel eastern ergs approaching the Nile River Valley. In contrast, the winds out of the northeast bring sediment from the southwest shore of the Red Sea. As one can see the Sahara several sediment sources supplying it.

Now that the modern Sahara Desert has been sufficiently described it is important to examine some of the factors that led to this area's transformation into a desert over long periods of time. Several geologic factors have contributed to the desertification of the Sahara region during the Cenozoic (Cooke et al 1993). First, through motions of the African Plate, this region slowly moved north to its present location in the dry sub-tropical latitudes at 20 to 30 degrees North of the equator. In addition to this movement of the African Continent, the rise of the Tibetan Plateau during the Late Tertiary to Quaternary drastically affected world climates. In the case of the Sahara region, this uplift helped to create the easterly jet stream of dry, subsiding air that causes the majority of erosion in the western and central Sahara Desert.

Yet another cause for this region's high erosion rate was the latest global cooling period. During the last glaciation the build-up of the polar ice caps created a steeper temperature gradient between the poles and the equator. This difference led to an increase in the velocities of the tradewinds, therefore eventually raising erosional rates. This glacial period also contributed to a cooling of ocean surface waters which may have reduced the amount of evaporation in lower latitudes and thereby reduced the amount of precipitation (Cooke et al., 1993).

The climate trend of increasing aridity can be interpreted from Pleistocene sediments in cores from the western Atlantic Ocean and African lakes. Aeolian turbidites, found in cores from the Atlantic ocean (Cooke et al., 1993) as well as other similar dust deposits in ocean cores indicate intermittent wet/dry periods trending towards longer dry periods during the last glacial period. It was during this time that active dune formation and desertification became prominent in this area. This period can also be interpreted as the time period when much of the modern Saharan sediment was generated; this sediment has been reworked during the current interglacial period.

From lake sediment cores it is evident that northern Africa underwent a prolonged wet period during the end of the last glacial period (~12,500 ya) which lasted until ~5,000 ya and peaked around 9,000 ya. Since then precipitation levels have continued to decline to the present arid environment. All of this information indicates a series of climate changes leading up to the present Sahara Desert.

Deserts of the Future

As seen in the previous section on the Sahara Desert desertification usually occurs as the environment of a certain area reacts to both geologic and climatic changes. What is not more commonly known is the fact that these reasons are not the main force causing desertification in certain regions today. Processes such as environmental change through plate movements take millions of years to turn once thriving landscapes into arid, moisture starved deserts. It has only recently come into light (in the past 40 years) what the main source of modern desertification is in respect to modern times, human beings.

Desertification, as defined by Thomas and Middleton (1994) in their book Desertification: Exploding the Myth, is "the ultimate step of land degradation, the point when land becomes irreversibly sterile in human terms and with no respect to reasonable economic limitations." In other words people living in semi-arid lands must farm in order to survive which results in the exploitation of the land to the point of rendering it useless. The main causes of desertification, which will be discussed in the following paragraphs, include overgrazing, overcultivation, irrigation mismanagement, deforestation, and urban and industrial activities, all of which arise from the problem of overpopulation.

An example of present-day desertification is taking place in the semi-arid area south of the Sahara Desert known as the Sahel (Thomas and Middleton, 1994). One of the most important factors is that the area has been inhabited for at least 600,000 years. It has also been exploited for decades for rich mineral resources and precious gum-bearing trees. One cause for the many problems in the area is the overgrazing of lands. This results in overconsumption by livestock, trampling plants and root systems, and consumption of undergrowth and seedlings, which eliminates new plants, natural fertilizers, and the vital anchoring system for soils, which help to hold in moisture. In addition to livestock, man has increased the problem through the use of advanced firearms. Natural predatory species of the area have been all but eliminated to protect the herds. This is slowly destroying the food chain and causing further proliferation of plant eating species therefore eliminating more plants. This process results in land that is close to barren while livestock herds are simply moved to a new area to begin the process all over again.

Another problem aiding in the desertification of the Sahel is deforestation (Thomas and Middleton, 1994). This area has always been known for its acacia trees which have provided the people with a fuelwood as well as a gum resource. One main problem is that the main fuel in this area is still wood. As the population continues to increase more and more wood has to be consumed to provide heat and a cooking source. In addition to this, thousands of hectares are cleared each year for agriculture which itself is a major problem. This deforestation process causes increased soil erosion rates and lower moisture retention rates without the tree root systems to strengthen the soil.

Agriculture is necessary to adequately sustain a growing population, but overcultivation in the semi-arid Sahel region has more of a negative effect. First of all, peoples in this area do not have enough modern farming techniques to either reduce factors such as soil erosion and nutrient depletion, or to shorten the fallow period (Thomas and Middleton, 1994). Second of all, mismanagement of irrigation techniques leads to increased soil runoff and depletion as well as lowering of the water table which does not have a fast recharge rate.

Desertification is a modern problem in more areas than just the Sahel. As populations increase and food supplies become scarce, more food must be produced. The encroachment of agriculture into moisture starved areas such as the Middle East, the American Southwest, and parts of China, to name a few, has increased the stresses on delicate environments to provide more resources than they can sustain. If indigenous peoples are not careful these semi-arid lands will quickly become depleted ; in the past such changes have only resulted in drought and famine. Only through careful land management, water conservation, and reforestation will these areas be able to survive.

Conclusion

Across the globe deserts provide and excellent insight into sedimentary and climatic processes. Ancient desert deposits such as the Navajo Sandstone provide an excellent example of past erosional processes that can be correlated with modern examples such as the Sahara. Extensive desertification aided by human exploitation shows that the human race is indeed altering the Planet. Overall, deserts are amazing landforms which are and integral part of the geologic process.

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